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Development and field experience of monitoring system for valve-regulated lead–acid batteries in stationary applications

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Abstract

With ever-evolving information technology, it is becoming increasingly important to secure reliable back-up power supplies in telecommunications networks, data-processing facilities, utilities, etc. While valve-regulated lead–acid (VRLA) batteries are predominantly used nowadays, their diagnosis technology is not fully developed. As partial-discharge techniques require temporarily shutting-down of the system and also degrade battery life, manual testers based on an ohmic techniques have become popular. Accordingly, the Battery Condition Watcher (BCW) has been developed and commercialized. This is an automatic monitoring system with remote communication capabilities. It measures the internal impedance, voltage and temperature of individual cells or batteries with high accuracy. These parameters are subjected to data processing to enable diagnosis of battery conditions and life. Some aspects of field usage of the BCW are reported.

Keywords: Valve-regulated lead–acid; Impedance; Diagnosis; Monitoring; Battery degradation

1. Introduction

Accounting for around 90% of the industrial lead–acid battery market in Japan, valve-regulated lead–acid (VRLA) batteries are used for stationary applications such as back-up power sources in telecommunications networks, data-processing facilities, utilities, mass transportation, and emergency devices. With recent advancements in information technology, back-up power utilization has rapidly diversified into various applications including distributed outdoor installations and remote terminals. While reliability is one of essential issues in back-up power, diagnosis and monitoring technology for VRLA batteries is not fully developed. Traditionally, discharge methods are utilized to obtain the reliable and accurate information on the state-of-health (SoH) or life of a VRLA battery [1]. These are, however, practical constraints such as temporarily shutting-down of the system and the testing of individual cells at a large expense of manpower. In telecommunications networks incorporating programmed partial-discharge techniques, in which, for example, 30% discharge takes place automatically a few times a year, repeated discharges deteriorate the life of VRLA stationary batteries [2,3].

As alternatives to discharge ohmic methods, impedance or conductance measurements can be used to estimate SoH by applying a small current and without circuit shut-down. While manual ohmic testers are popular in practice [4], automatic continuous monitoring is becoming adopted to provide not only monitoring accuracy but also to meet economic and technical requirements such as inertness against electrical noise. Accordingly, the integrations of remote monitoring and diagnosis into information technology networks is now feasible [5].

The Battery Condition Watcher (BCW) system [6], a type of impedance method, has been developed and commercialized for monitoring and diagnosing VRLA batteries and related devices. The technical details and field experience are described below.

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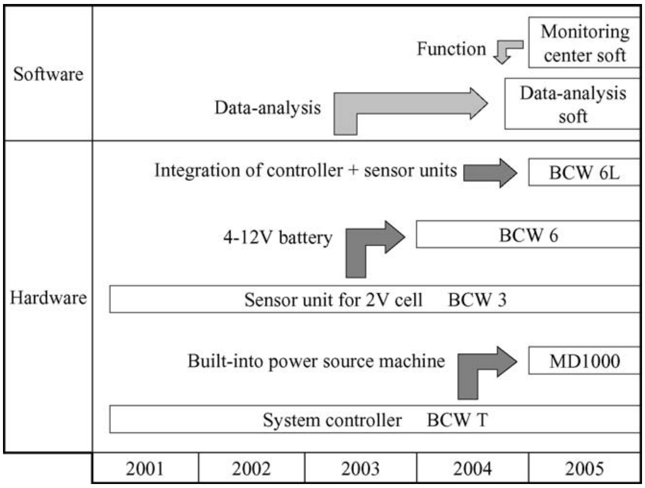
Table 1
Evolution of BCW technology



2. Evolution of BCW

As seen in Table 1, the BCW was first developed as a set of system controller (BCW T) and sensor units for 2 V cells (BCW 3), which were primarily applied to 48 V telecommunications networks [6]. The BCW measures cell internal impedance, voltage and temperature. These followed the BCW 6 system for 4–12 V monobloc batteries. The BCW 6L was a functional integration of a sensor unit and a controller that can be incorporated into small-size devices such as uninterruptible power supply (UPS) systems.

As many as a few hundreds of BCWs were connected into a network system with LAN and monitoring centres. The latest development is the MD1000 unit that is an integration of power source machine and system controller to perform monitoring and controlling of both devices and batteries.

3. Deterioration of VRLA batteries

As seen in Fig. 1, the capacity of a VRLA battery tends to increase slightly for a few years after the start of use, but then decreases gradually with the passage of time. Approaching the end of service life, the capacity decrease generally accelerates. This characteristic varies greatly depending on the environmental and operational conditions such as temperature, float-charge voltage, and cyclic usage. The internal impedance, on the other hand, is virtually unchanged during the early period of battery service. Then it starts to rise at a rate that is enhanced with the time of use.

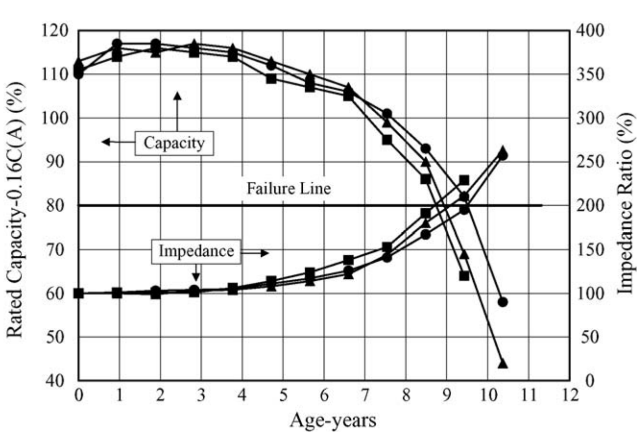


Fig. 1. Change of capacity and impedance of MSE battery during life.

The conditions or SoH of individual cells or batteries can be monitored by continuously measuring their impedance, which enables prediction of the end of service life and allows the preparation of replacements for failing cells or batteries.

4. Requirements of BCW

4.1. Measurement

As mentioned above with respect to Fig. 1, there is a deterioration level that indicates the end of battery life. This is recognized as about 1.5–2 times the initial value. In order to detect and estimate the degree of deterioration, an impedance sensor is required with high resolution and stability, for which the measurement of cell voltage and temperature is particularly useful.

Since a battery string consists of multiple cells or batteries connected in series, it is the cell or battery with the lowest capacity that controls the capacity of the whole string. Therefore, it is obviously essential to monitor individual cells or batteries.

4.2. Monitoring

It is of great importance that the BCW is designed to allow easy monitoring with as little manpower as possible. The BCW is required to check battery condition remotely and to store and analyze the measured data by using personal computers. This is performed through a network such as the Internet.

4.3. Construction

Although it is desirable to incorporate the BCW at the time of battery installation, there is a demand of after-installation. It is therefore necessary that the BCW is small and easy to install without having to modify existing rectifiers and battery cabinets.

5. System configuration

The BCW consists of battery sensor units and system control units, as seen in Fig. 2. The units are linked together via multi-drop communication.

5.1. Battery sensor unit

The BCW 3 sensor units measure the impedance and voltage values of 13 cells and the temperatures of 4 cells. Impedance measurement is performed by means of Kelvin the method which must be accomplished on-line with high accuracy and at low cost. The following requirements need to be addressed.

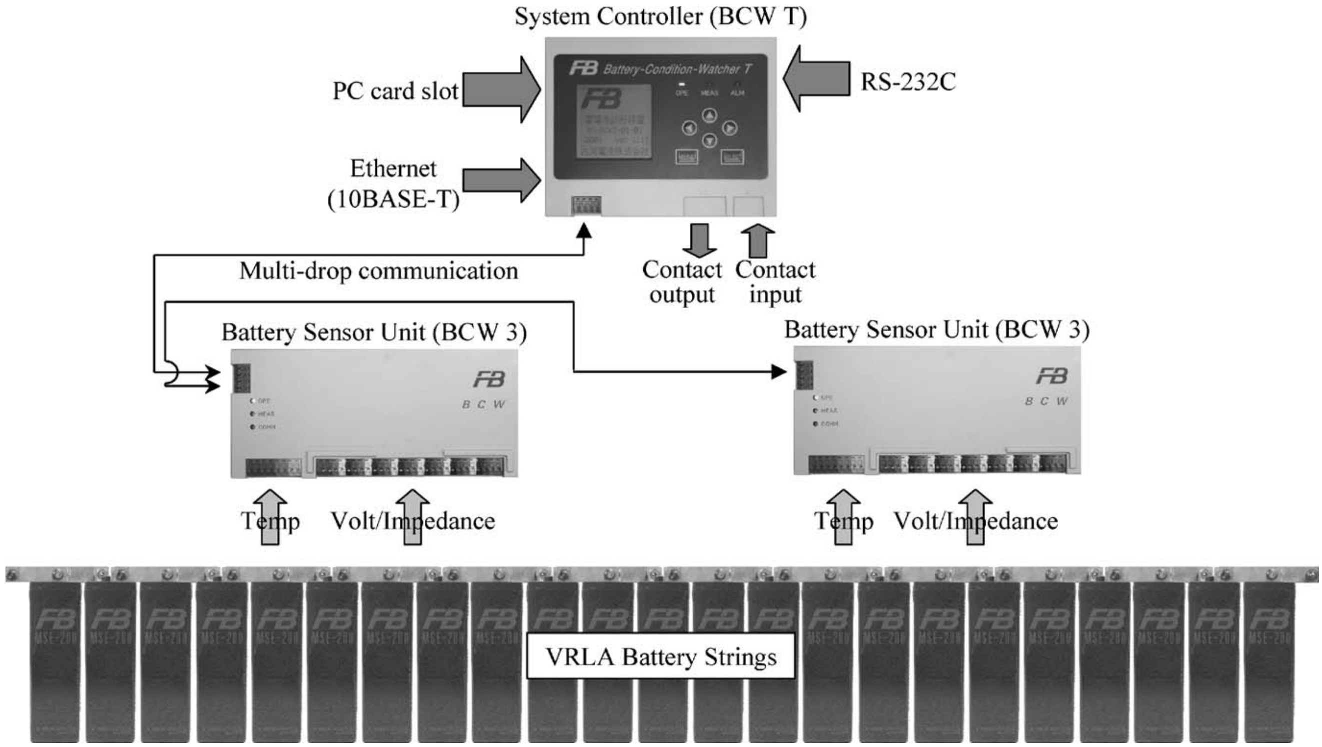


Fig. 2. System configuration of BCW.

- The deterioration of the battery can be ascertained.
- The weak electromotive force from the battery can be measured with high accuracy. For instance the initial value of a VRLA of the MSE500 type (500 Ah, 2 V) is as small as about 0.3 mΩ and generates only 0.3 mV at a measurement current of 1 A.
- Stable measurements can be achieved even if a noise current is flowing into or out of the battery charger or devices connected to the battery.
- The measuring current should not divert into batteries other than the battery under measurement or devices connected to the battery, to prevent the occurrence of errors.
- The instrument itself is capable of maintaining stable measurements for extended periods of time.

To meet the above requirements, the following measures were taken.

5.1.1. Measurement frequency

The frequency response characteristic of a MSE cell is shown in Fig. 3, in which the resistive factors are demonstrated to vary with frequency. In the lower end of the frequency range, the major process is diffusion which is believed to have little correlation with battery deterioration. Through 1–100 Hz, there are resistances due to both ohmic conductivity (ionic and electronic) and charge-transfer processes, which are directly related to battery deterioration. Over 100 Hz, the imaginary part due to Faradic processes is predominant. Thus, the measurement frequency is taken from 1 to 100 Hz.

5.1.2. Diversion of measuring current

When the current is applied to multiple cells in series, as seen in case 1 of Fig. 4, the system is more simply configured than in case 2 where the current is applied to a single cell. On the other hand, the amount of measuring current flowing into a circuit other than the battery to be measured will increase, depending on the impedance distribution among the batteries, charger and connected devices (load), and thereby will greatly affect the measurement. To minimize such effects, it is decided to adopt the method in which the current is applied to individual cells.

5.1.3. Noise countermeasures

Noise current may be so great in some cases that it becomes difficult to keep the size and cost of the BCW reasonable.

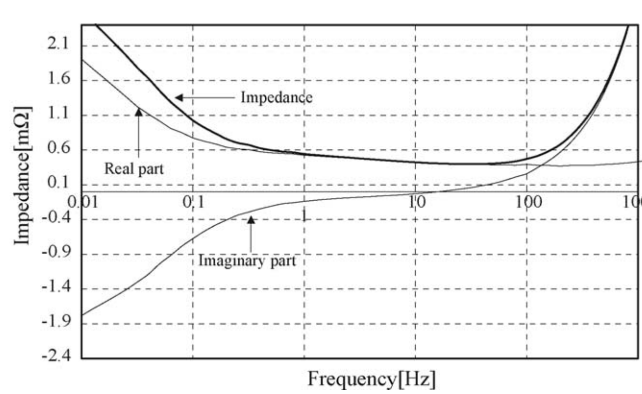


Fig. 3. Frequency characteristic of impedance of MSE battery.

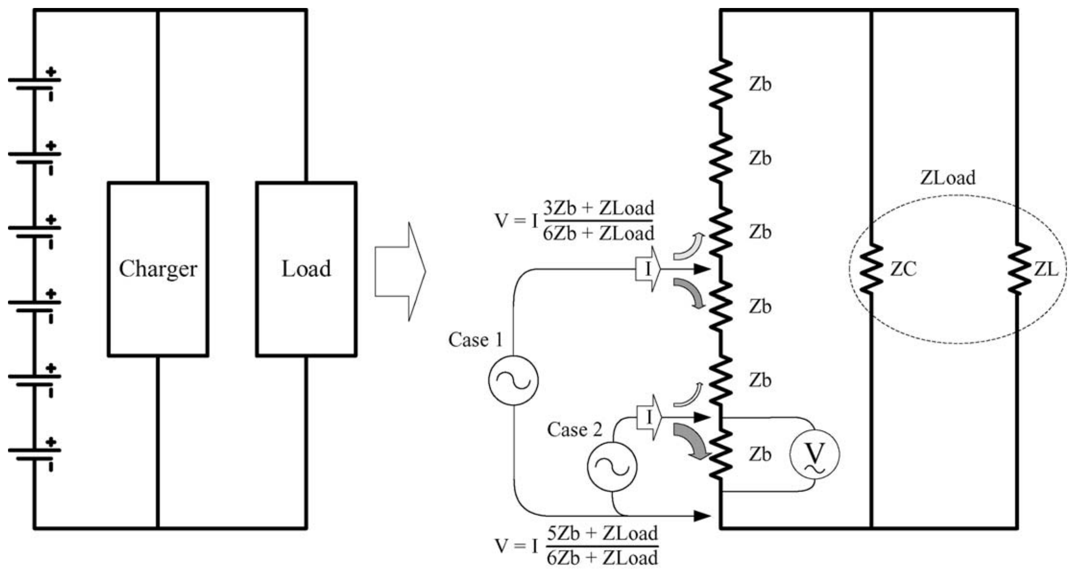


Fig. 4. Diversion of measuring current.

A frequency filter is incorporated on the signal pick-up side to separate the noise and measurement currents. It consists of an analog band-pass filter and a software-based digital filter.

5.1.4. Stabilization of measurement

The characteristics of the components of BCW circuits vary with temperature and time. It is therefore necessary to make appropriate corrections to obtain stable and reliable outputs. In the input, a switch circuit is provided and the impedance is determined from the ratio of the measuring current to the resulting electromotive force of the battery obtained by making measurements at various time interval. Variations can be suppressed by the use of the same circuit, which thereby enables measurements to become stable.

The resulting sensor circuit is given as a block diagram in Fig. 5.

5.2. System control unit

This is the main controller of the BCW, and undertakes control of battery sensors, data storage, screen display, alarm control and communication with external equipments.

5.2.1. Circuit configuration

A block diagram of the system control unit is given in Fig. 6. It consists mainly of a 32 bit RISC CPU, a graphic panel circuit, memories, communication interface circuits, contact input/output circuits, a real-time clock, a power source circuit, and a PC card interface that is especially advantageous to add functions without changing the hardware.

5.2.2. Software configuration

Task programs including measurement, display, alarm, network communication (TCP/IP, HTTPd, SMTP control, etc.) and file system can be run on the real-time OS.

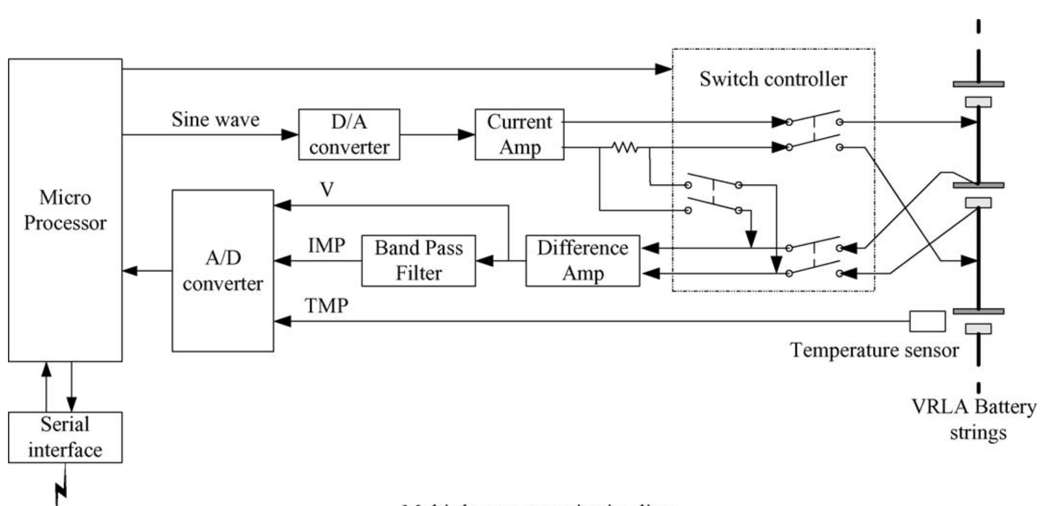


Fig. 5. Block diagram of BCW sensor unit.

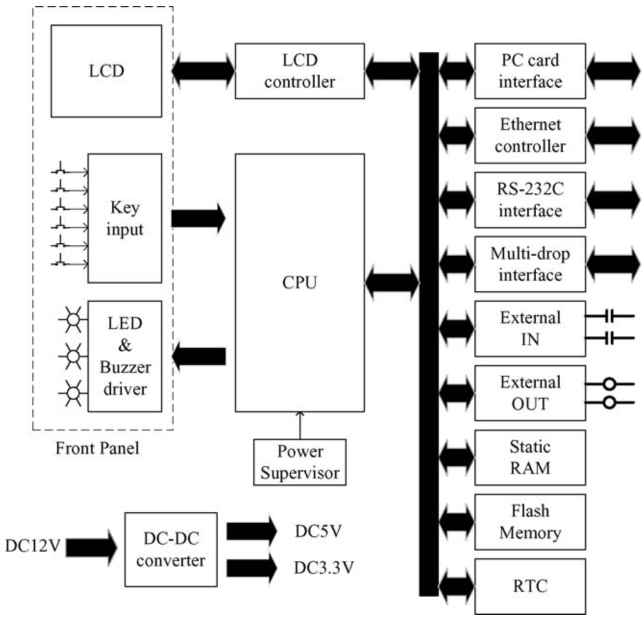


Fig. 6. Block diagram of BCW control unit.

5.2.3. *Form of monitoring*

In order to facilitate the monitoring, the following procedure is adopted.

- Checks at installation sites. All data obtained and monitoring history can be displayed on a LCD. When a measured value deviates from the specified allowable range, an alarm lamp comes on and its identity is displayed on the LCD. Past data are written in a CSV-type file by inserting a flash ATA-type PC card into the socket of the control unit. Since the CSV-type file can be read with a spreadsheet package such as EXCEL, the data can be represented in such form as a trend graph for visual checking.
- Checks of remote locations. Monitoring can be conducted on the Web through Ethernet. The data can be displayed by an appropriate Internet browser without any special software. As with the LCD display function, all data and past measurement records along with alarm records can be displayed. The major specifications and examples of system installation are reported elsewhere [6].

6. Results and discussion

Before commercial usage, field trials were undertaken for two years; the results have been published previously [6]. Both the battery temperature distribution within an installation and its change over a given period were found to depend on the battery itself as well as operational and environmental conditions. The effect of temperature on impedance became more significant with the progress of battery deterioration. Another observation was that temperature correction performed through an algorithm can result in a smooth trend of increasing impedance without abnormality. Some aspects of field experience in commercial applications are described as follows.

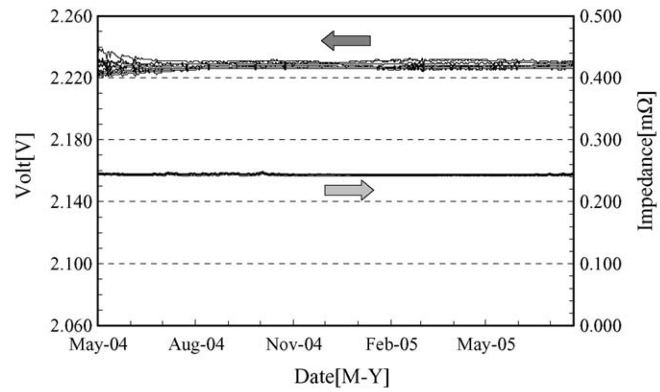


Fig. 7. Voltage and impedance trends of VRLA cells after installation.

6.1. *Typical features of impedance change through the use period*

For VRLA cells (500 Ah) with an expected life of 7–9 years, distinct differences are observed during the progress of battery deterioration. As seen in Fig. 7, the substantial distribution of cell voltages at the start of use gradually decreases and converges to a reduced range in several months. By contrast, the cell impedances remained not only stable without fluctuation but also showed negligible variation from cell to cell.

After two years of installation, the impedances were stable despite large temperature changes due to the absence of air-conditioning (see Fig. 8). Data for other VRLA cells (300 Ah) that have been in service for seven years are shown in Fig. 9. It is seen that the impedance rises gradually and that there is a remarkable fluctuation from cell by cell due to temperature changes. For, nine years old VRLA cells (500 Ah), the impedances of certain cells has risen steeply and there by resulted in a large distribution of values, see Fig. 10.

The above observations are consistent with what is experienced in former field trials with respect to relationship between VRLA impedance and battery degradation.

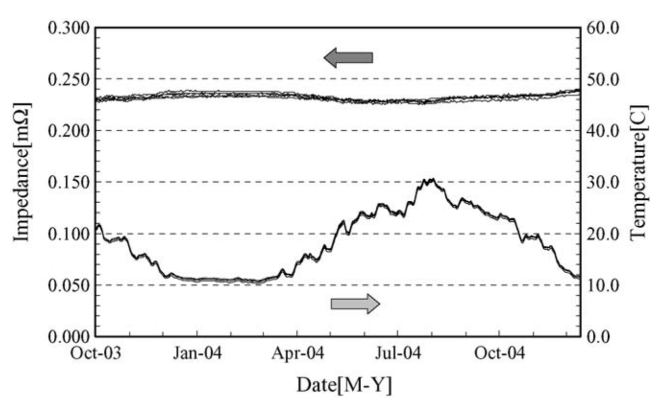


Fig. 8. Impedance and temperature trends of VRLA cells after two year of installation without air-conditioning.

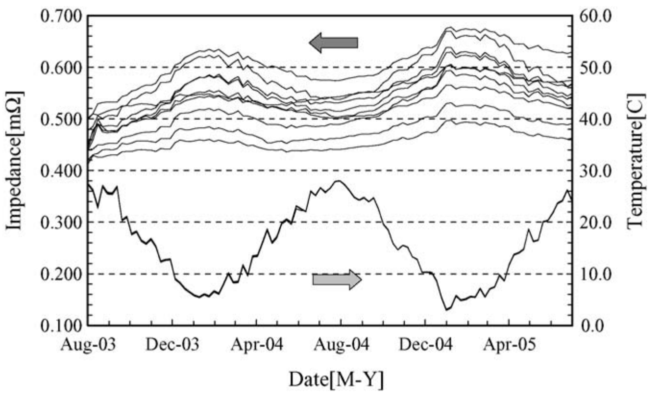


Fig. 9. Impedance and temperature trends of seven years old VRLA.

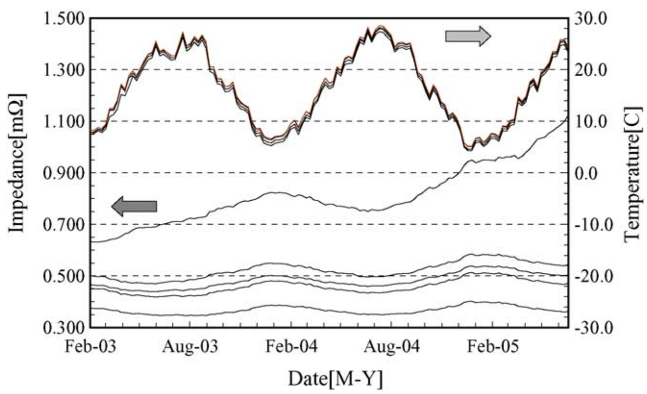


Fig. 10. Impedance and temperature trends of nine years old VRLA cells.

6.2. Investigation of failed cells

Capacity measurements have been performed on nine years old cells. The results are consistent with above impedance data, as seen in Fig. 11. One cell with less than 80% capacity was located on the top shelf of the cabinet where temperature was the highest, as seen in Fig. 12.

6.3. Examples of abnormality

The changes in cell voltages and impedances of VRLA cells (300 Ah) after one year of installation are shown in Fig. 13. One cell, with larger voltage and steeply increasing impedance, was detected as the first defect cell. For six years old VRLA cells (200 Ah), the voltage of one cell was irregular and its impedance behaviour was different from the others, as indicated in Fig. 16.

These examples demonstrate that continuous monitoring with the BCW can detect defective cells (Fig. 14).

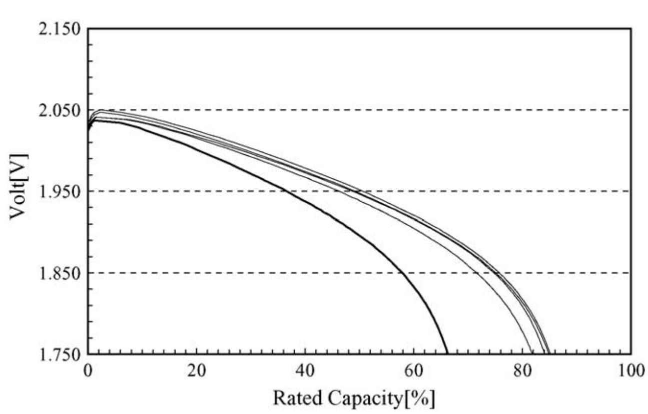


Fig. 11. Discharge capacities of nine years old VRLA cells.

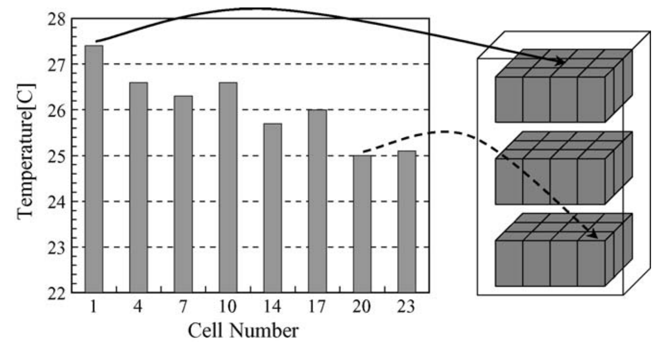


Fig. 12. Temperature distribution of VRLA cells of Fig. 11 in a cabinet.

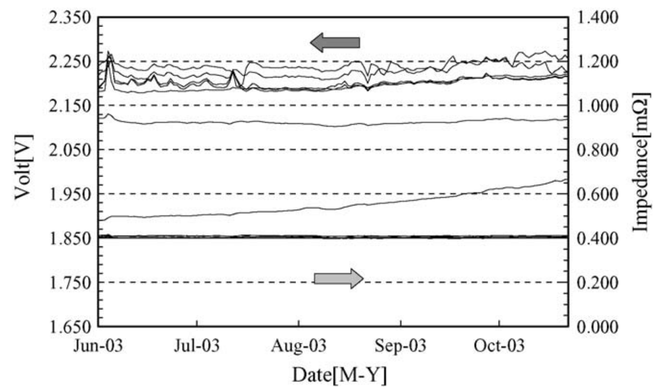


Fig. 13. Voltage and impedance trends of one year old VRLA cells.

6.4. Discharge behaviour

There are concerns over the premature capacity loss (PCL) of batteries during stationary usage. This was reported to be due to the float-charging system undergoing cyclic duty [2,3,7,8]. Such a situation is shown in Fig. 15. By adding a function of voltage–time measurement to the BCW, the discharge behaviour

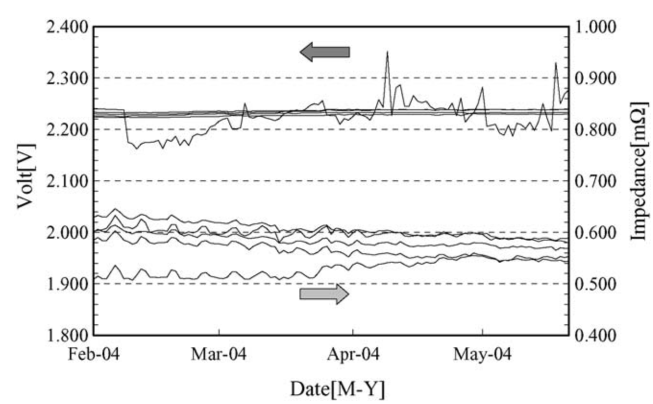


Fig. 14. Voltage and impedance trends of six years old VRLA cells.

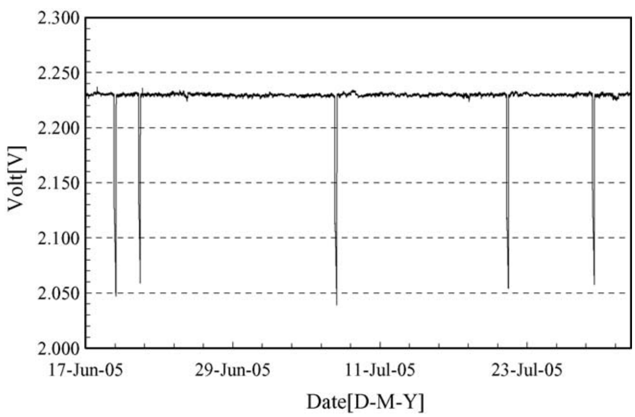


Fig. 15. Frequent discharge by a float-charge system.

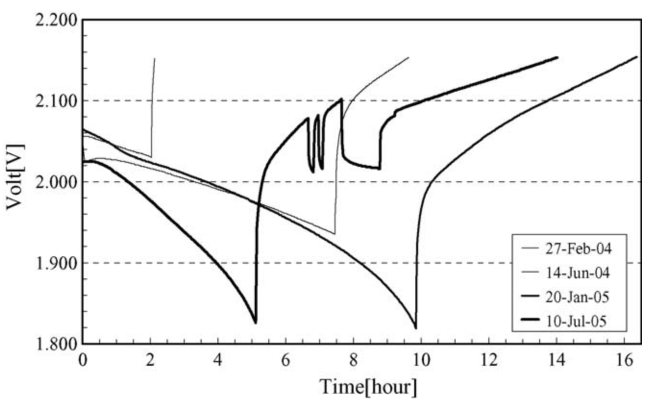


Fig. 16. Discharge behaviour in case of frequent discharge.

was monitored. As seen in Fig. 16, the discharge time becomes less on repeated cycling.

7. Conclusions

The family of BCW units and their integration into power source devices have been successfully developed and utilized in various stationary applications. Field experience over a few years has demonstrated the versatility of BCW technology to monitor and diagnose VRLA batteries, not only in terms of continuous SoH deterioration but also in a variety of abnormalities.

The performance of the BCW is derived from automatic and continuous impedance diagnosis of individual cells or batteries together with voltage and temperature, measurements. The BCW processes, stores and communicates the collected data and activates necessary alarms through a IT system.

From the battery manufacturer's point of view, accumulated data from field monitoring are essential for the design and development of highly-reliable VRLA batteries, as well as advanced diagnostic systems for their use.

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